Laser produced plasmas using cryogenic Xe for actinic metrology and inspection tools
– *effects of laser pulse length* –

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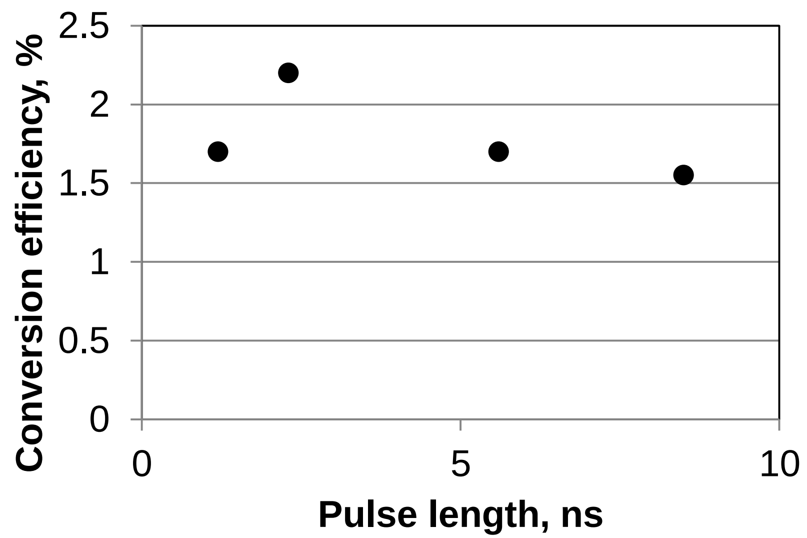
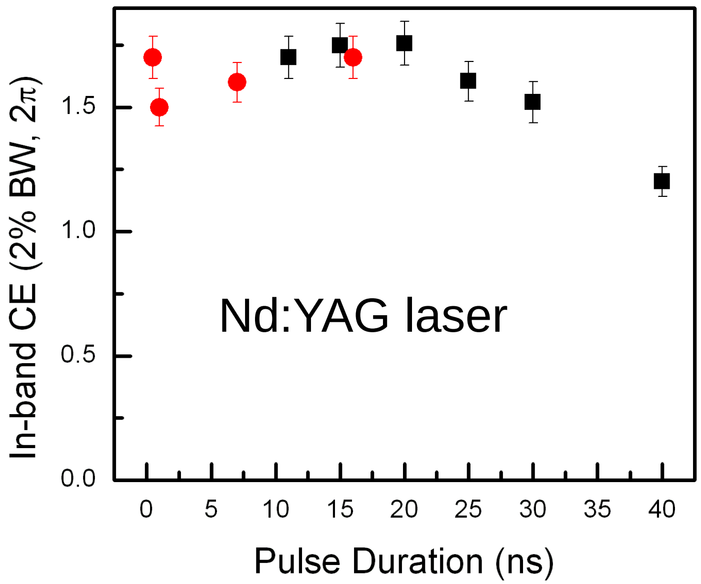
Conventional wisdom suggests short laser pulses provide the highest CE

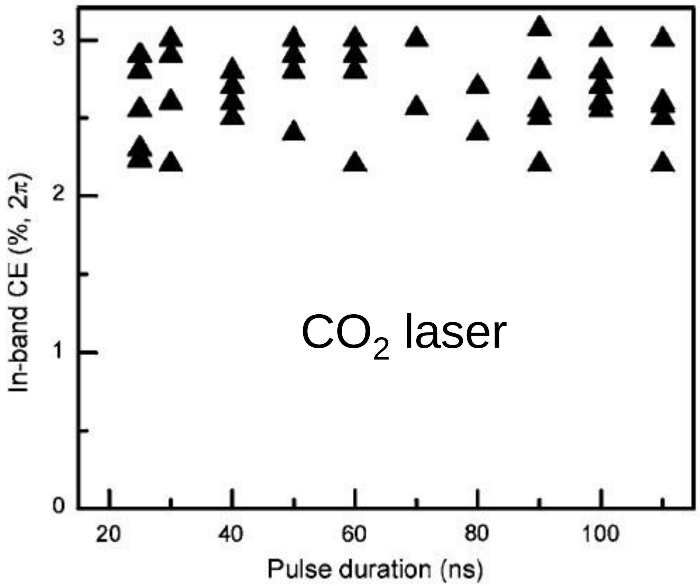
- Plasmas from shorter pulses have too small an emitting region.
- Coronal plasmas from long pulses have too much opacity.
- **And**, long pulses may lead to excessive motion of the emitting region.
- Early work done by Ando et al (Applied Phys Lett 89, 151501, 2006) concluded ~2 ns gives optimium CE.
- It depends on several parameters, (*e.g.,* spot size, plasma scale length)
- Ideal system pulse length may be different than optimum CE, considering cost, complexity and efficiency of system



Our results (1 and 10 μm on Sn) consistently showed that pulse lengths up to 30 ns provide adequate CE



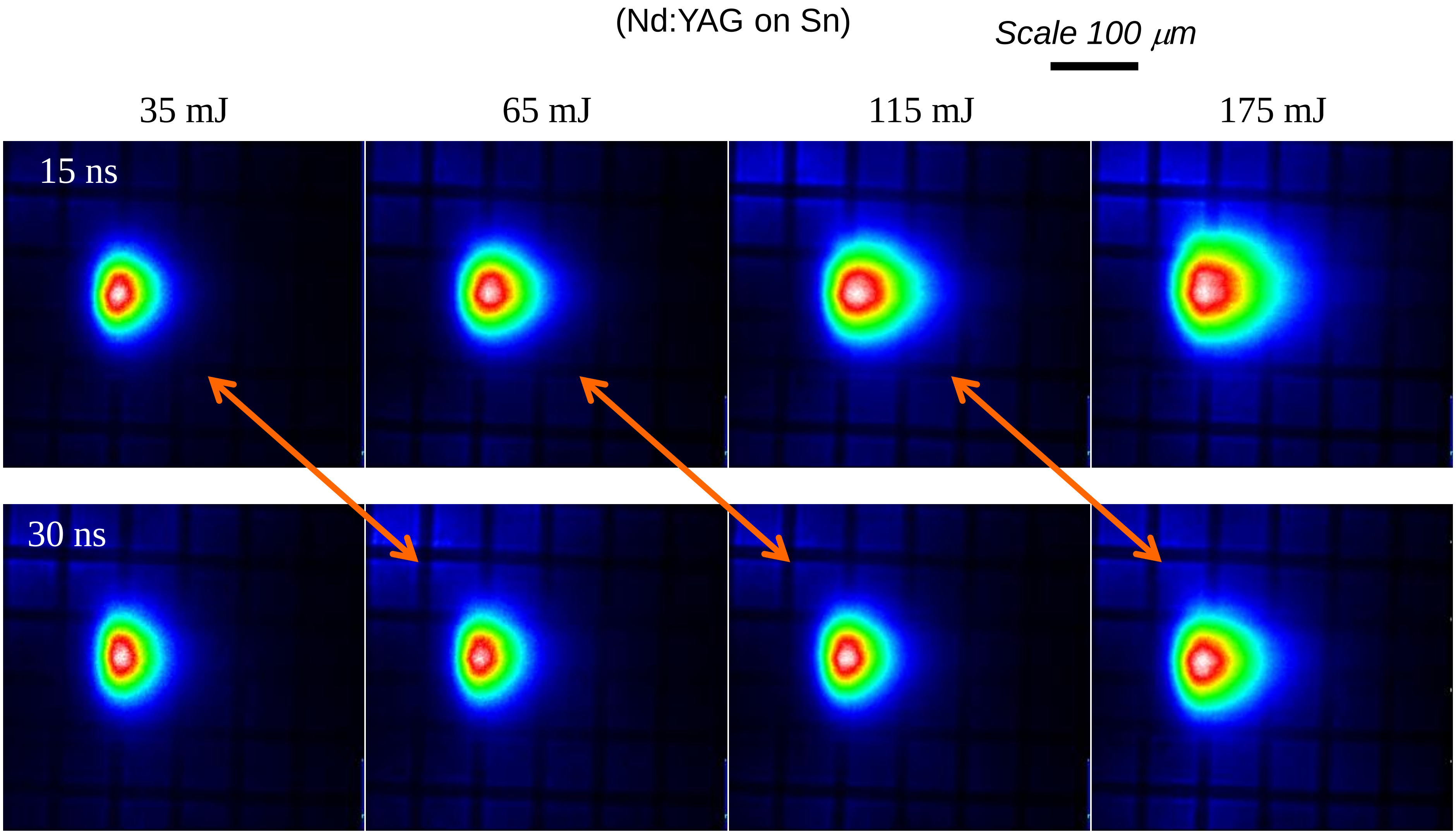
*Tao et al, Proc SPIE **7969**, 796930 (2011).*



*Tao et al, Appl Phys Lett **92**, 251501 (2008).*

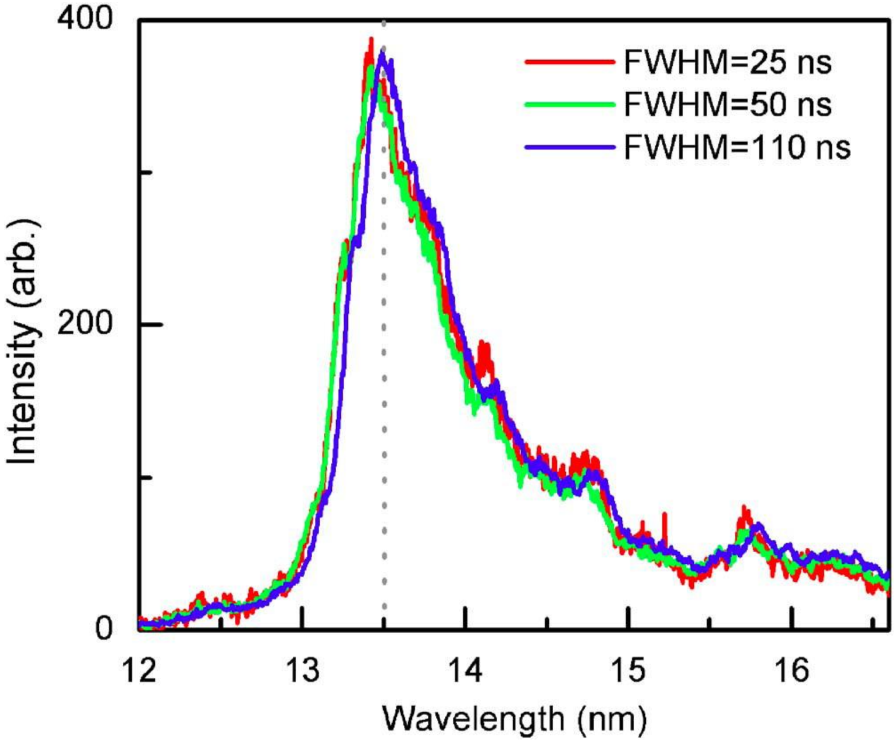
- Low density and non-isothermal expansion with a CO_2 laser.
- Not entirely clear why this is true for a 1 μm drive laser.
- Size and motion of emitting region also appears acceptable…

Experiments showed EUV source size depends more on *laser intensity* than on *pulse duration*

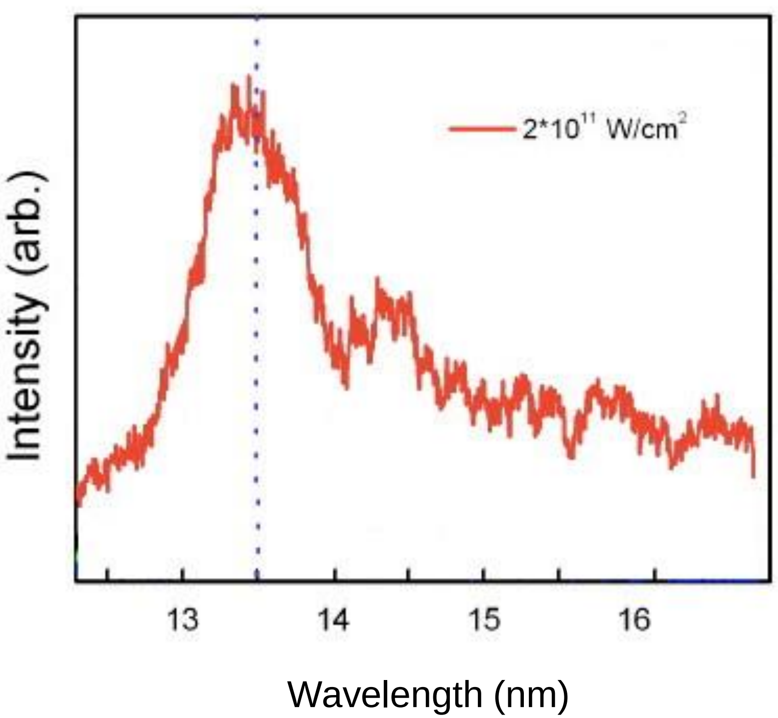


Spectra are independent of pulse length

CO_2 laser, long tail removed



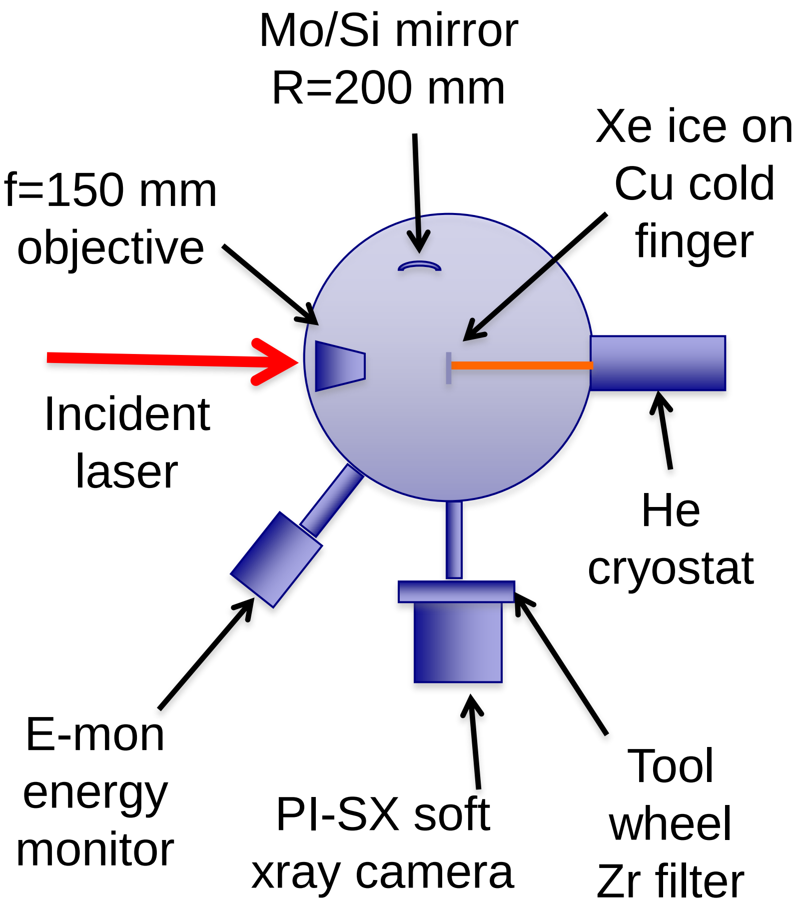
YAG laser, 10-30 ns range

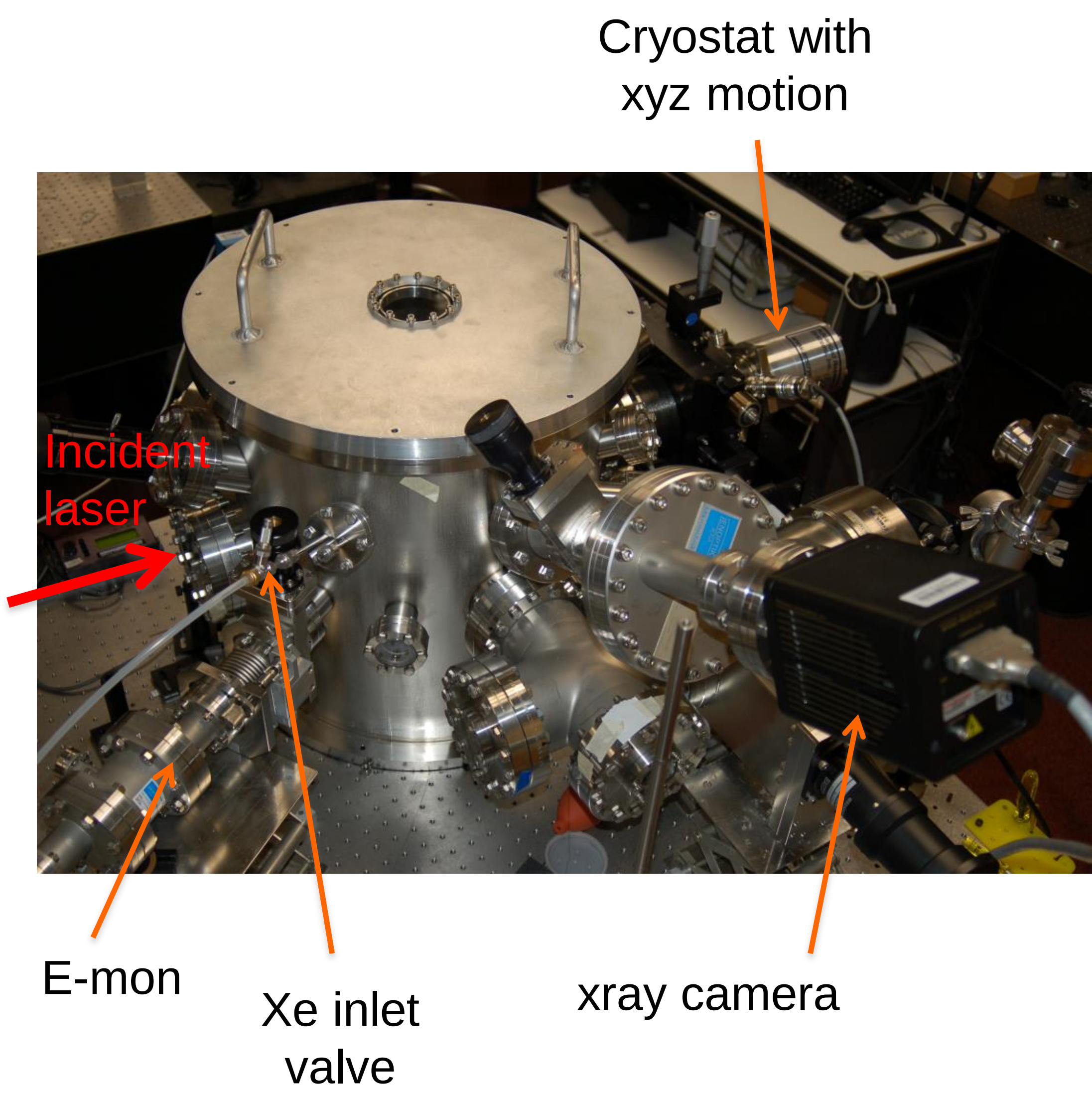


Background and goals of our current experiments

- For metrology, source requirements are driven by brightness, rather than power.
- With CE up to 1%, xenon is a practical target material, with advantages in debris management.
- Goals of our current experiments:
  - Characterize CE behavior and plasma size for varying pulse durations, using Nd:YAG laser on solid Xe target
  - Demonstrate conclusions obtained with Sn targets are valid

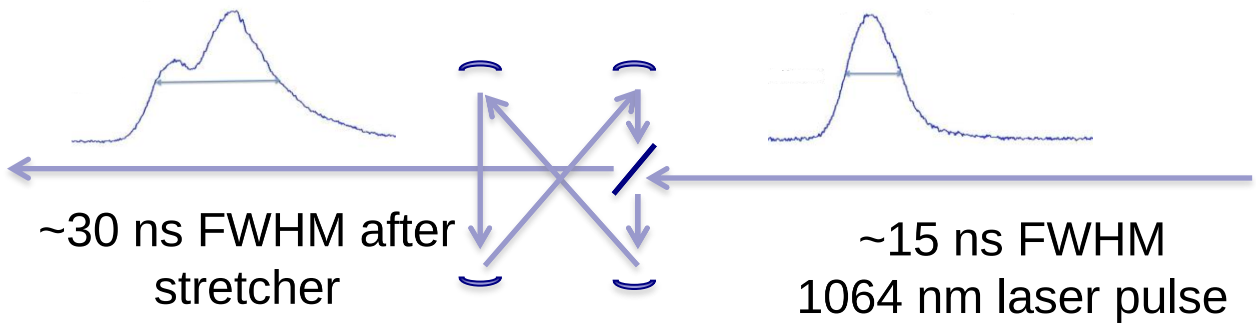
Experiment arrangement at UCSD

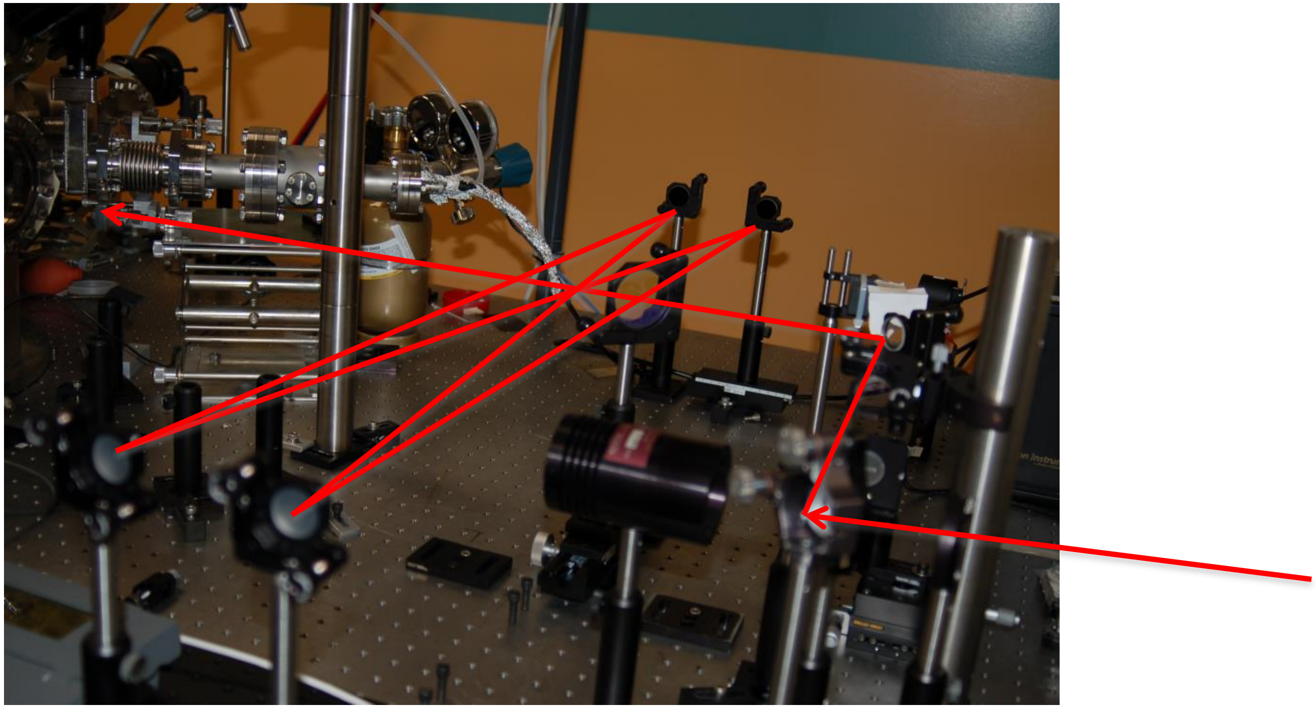




An optical pulse stretcher (delay line) was used

4 x f-500 mm mirrors , 1 beam splitter R/T=70/30, ~10 ns loop

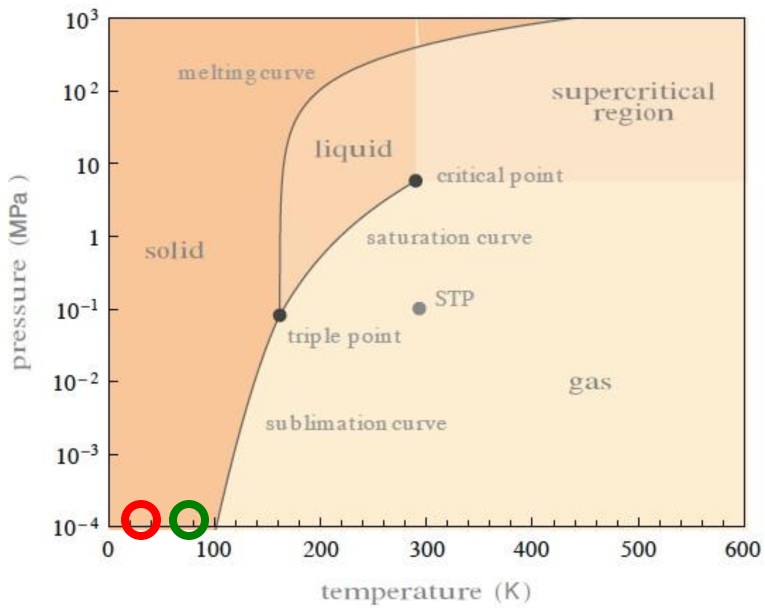


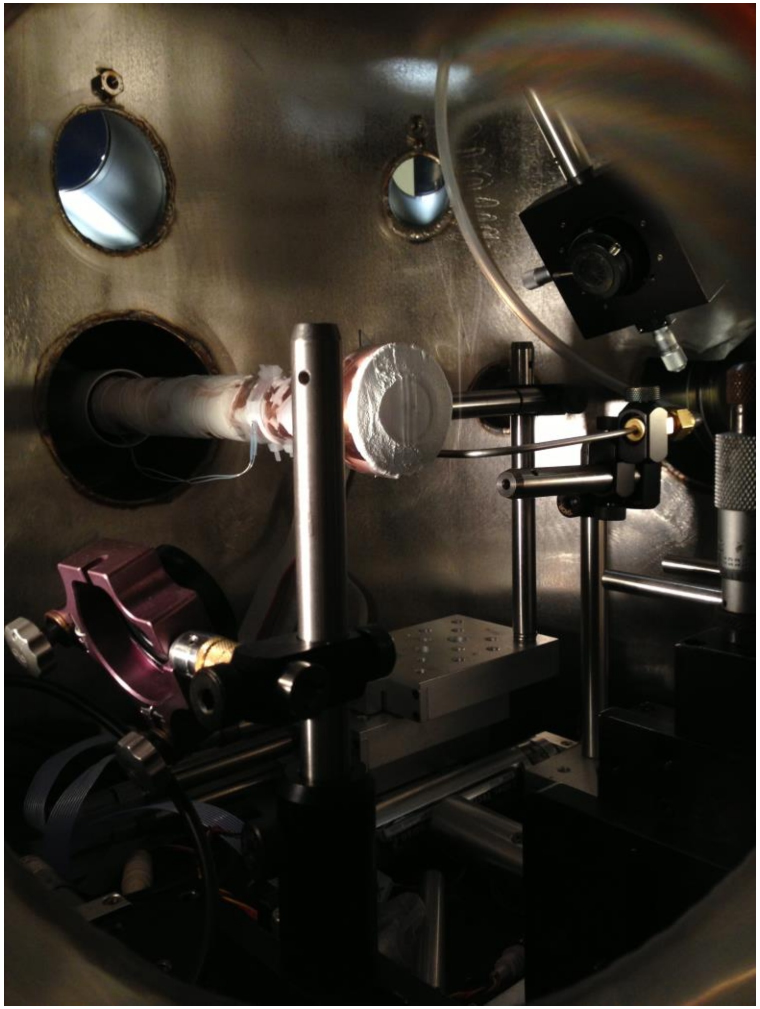


A. Burkert, J. Bergmann, W. Triebel and U. Natura, *Rev Sci Inst* **81** (2010) 033104.

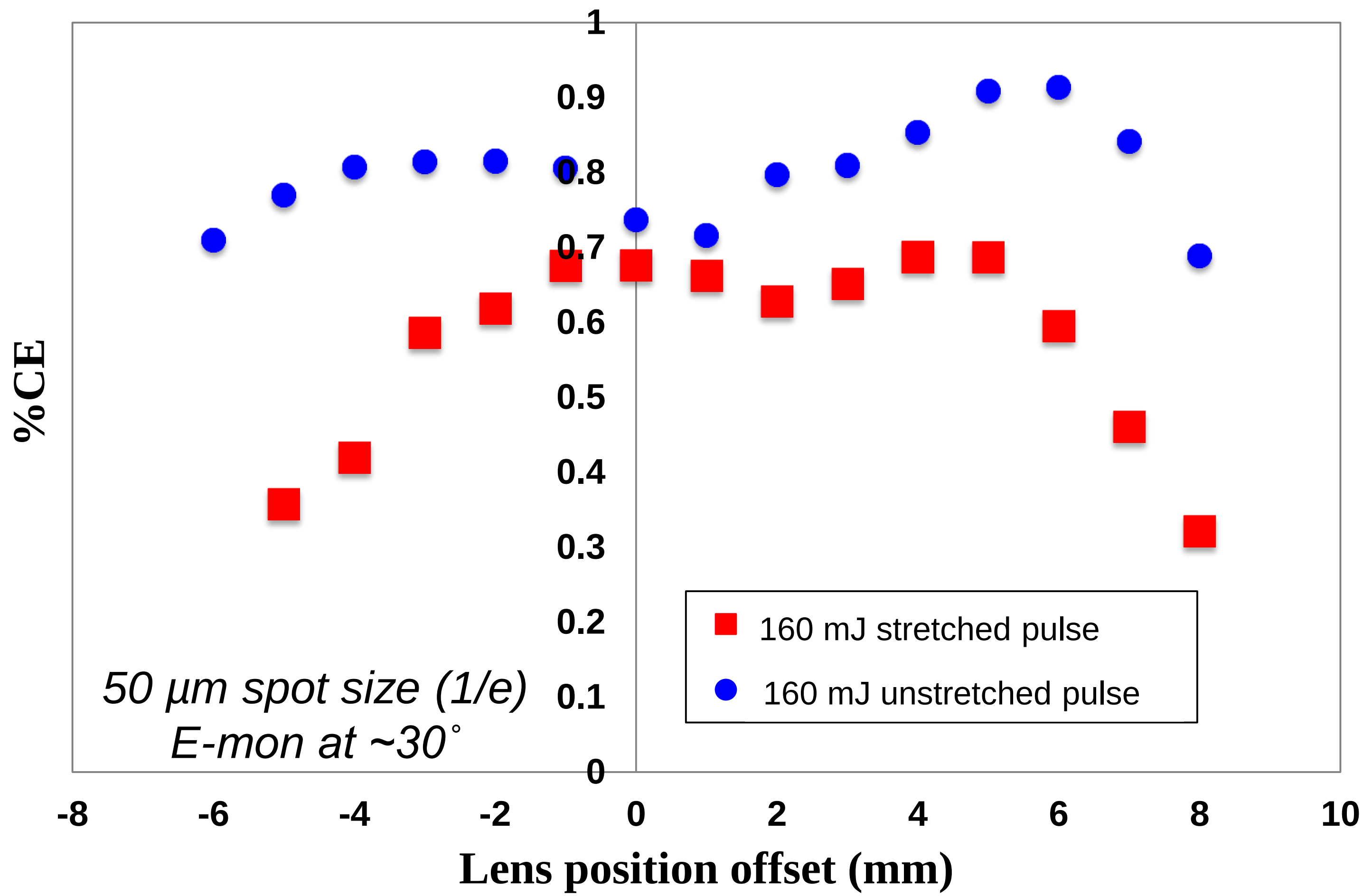
Experience with Xe ice

- Xe is pre-cooled and fed into the chamber through a tube pointed at the surface.
- Ice depths 0.1-1 mm are formed.
- Polycrystalline ice, density depends on thickness and growth rate.
- In the photo to the right, a scraper was used to flatten "*very thick*" ice layers.

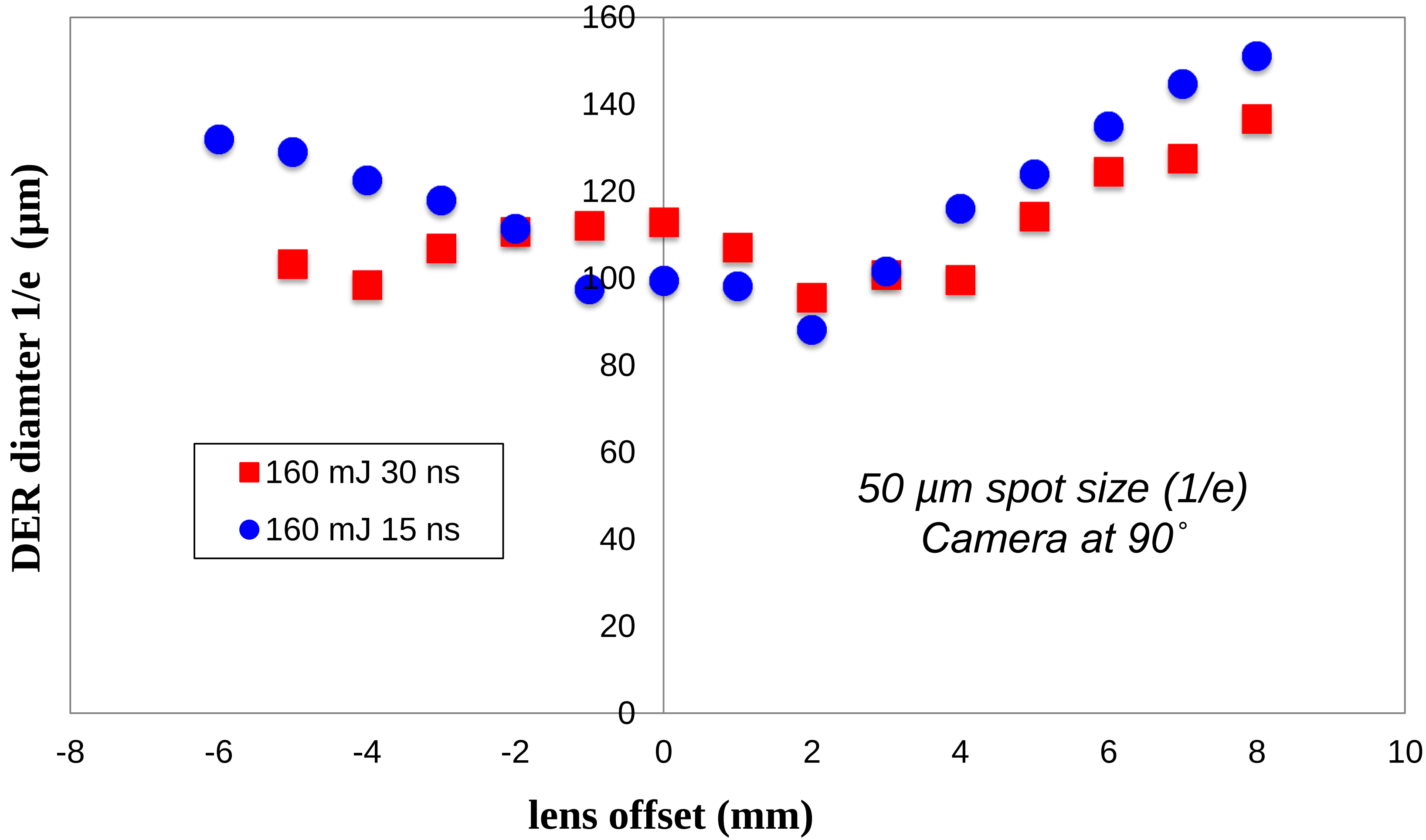




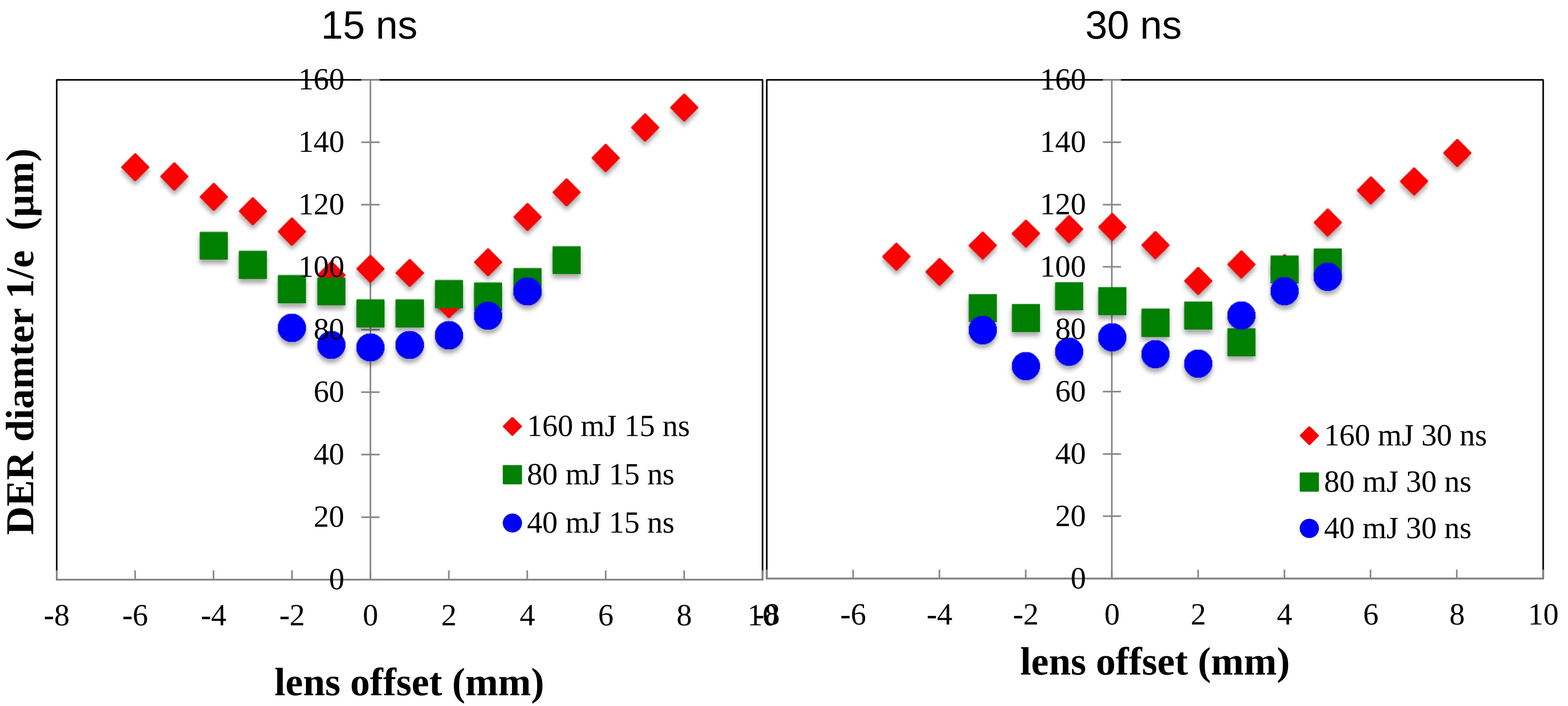
CE at best intensity drops by 10-15% with long pulse, consistent with earlier work



Time-integrated in-band emitter size does not increase much with pulse length, consistent with earlier work

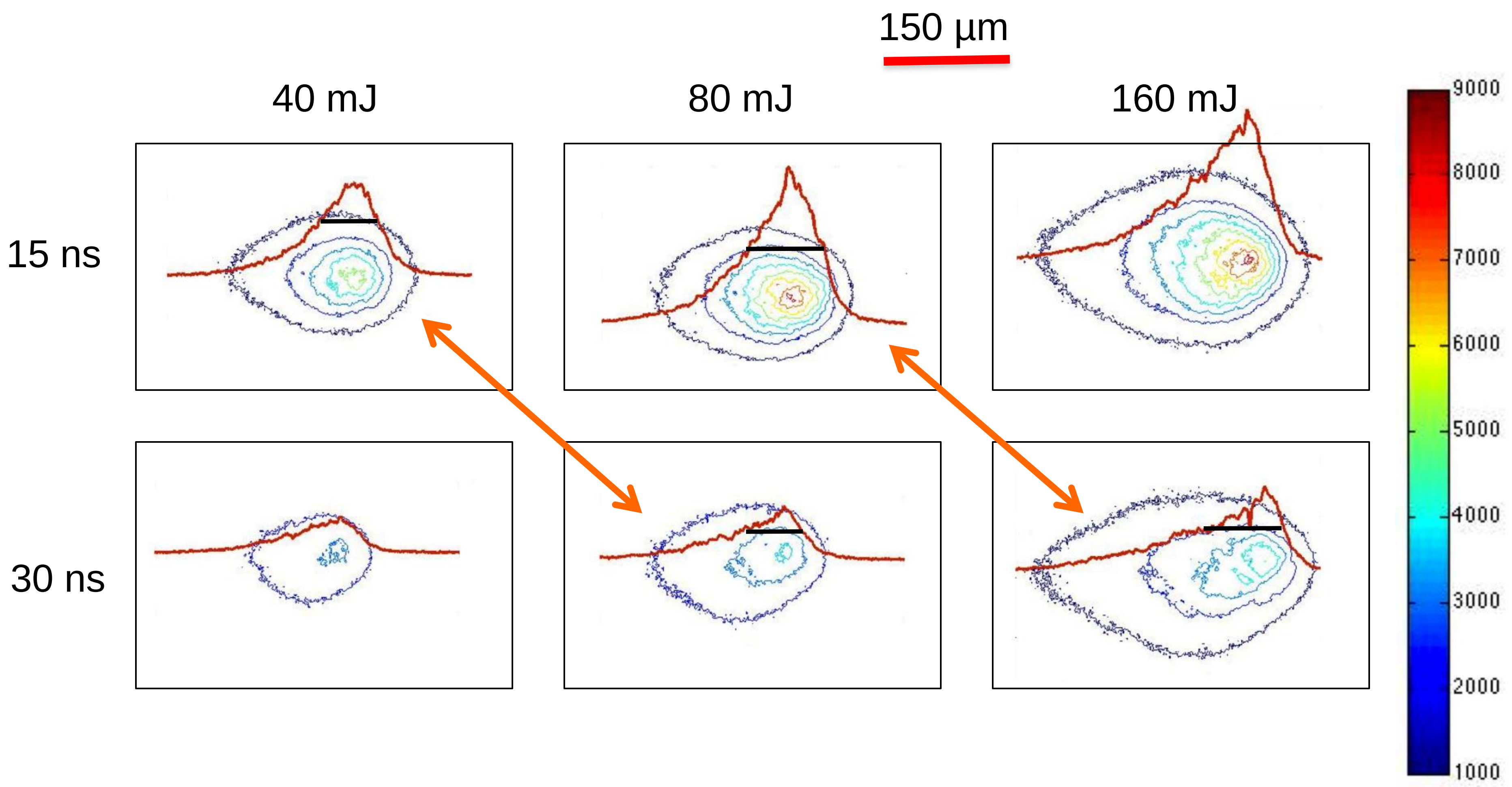


Emitter size increases with intensity, also consistent with earlier results



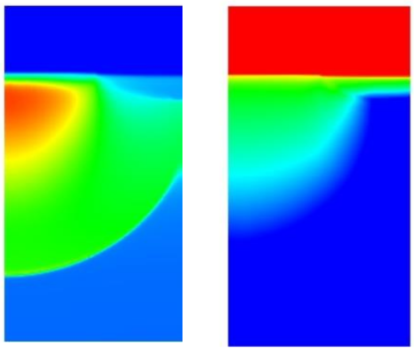
In-band plasma images at focus

50 µm 1/e spot size
(all images share a common scale)

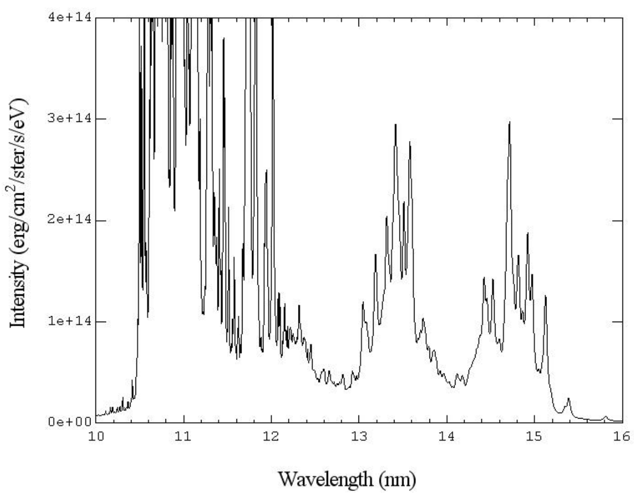


Simulations were performed at Prism Computational Sciences using their suite of numerical tools

- **HELIOS**: 1-D radiation-magnetohydrodynamics code
- **SPECT3D**: Imaging and spectral analysis package
- **PROPACEOS**: High-fidelity equation of state and multi-frequency opacity database
- **FLASH**: Multi-dimensional radiation-magnetohydrodynamics (Flash Center, U. Chicago)



Plasma temperature and density, 2D RZ geometry (FLASH)



Xe spectrum (PROPACEOS, SPECT3D)

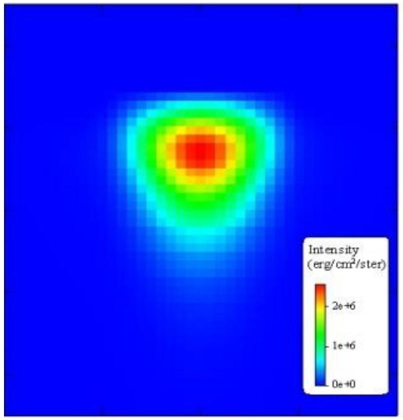


Image of 13.5 nm emission region (SPECT3D)

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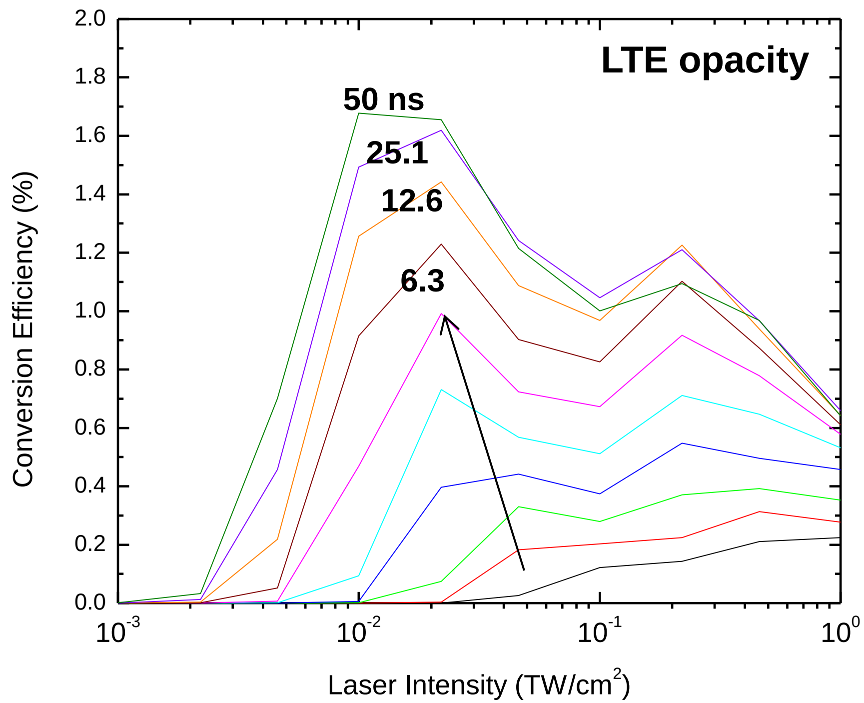
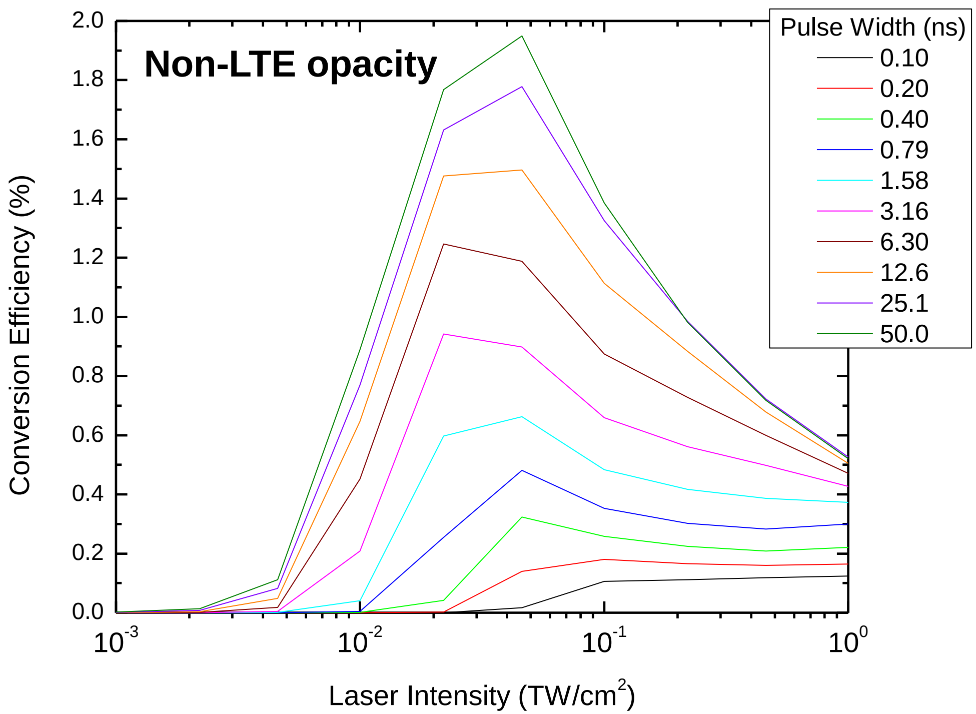
In-band (13.5 nm) conversion efficiency was modeled for various pulse widths using a 1D rad-hydro code

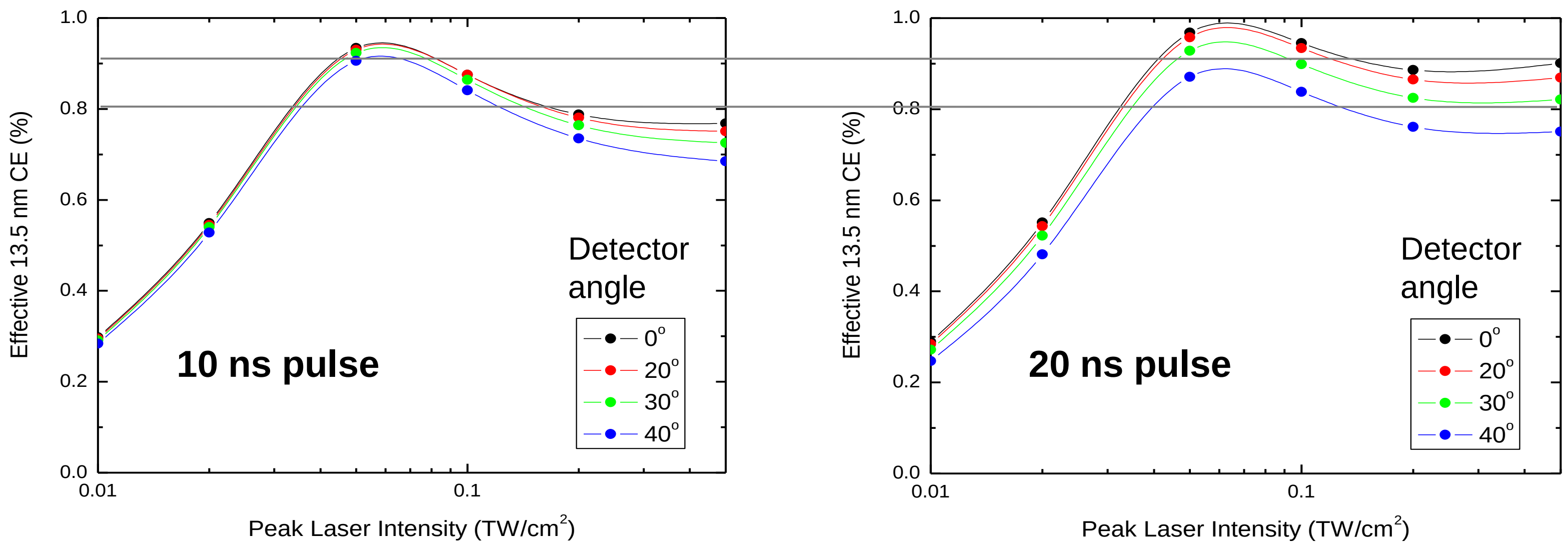
- Frozen Xe layer heated by 1.06 μm laser light
- Gaussian time profile of the laser beam
- Peak intensity varying from 1 GW/cm² to 1 TW/cm²
- Wide range of pulse widths from 0.1 ns to 50 ns





Post-processed 2D rad hydro results show small difference in optimum CE for 10 and 20 ns pulses

(Laser spot size = 100 μm/cm²)



- Very slight reduction in CE at 40˚ (same as experiments) as pulse length increases.
- Increase in CE at near-normal angles!

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Time integrated images at 40˚ confirm strong dependence of DER on intensity and weak dependence on pulse length

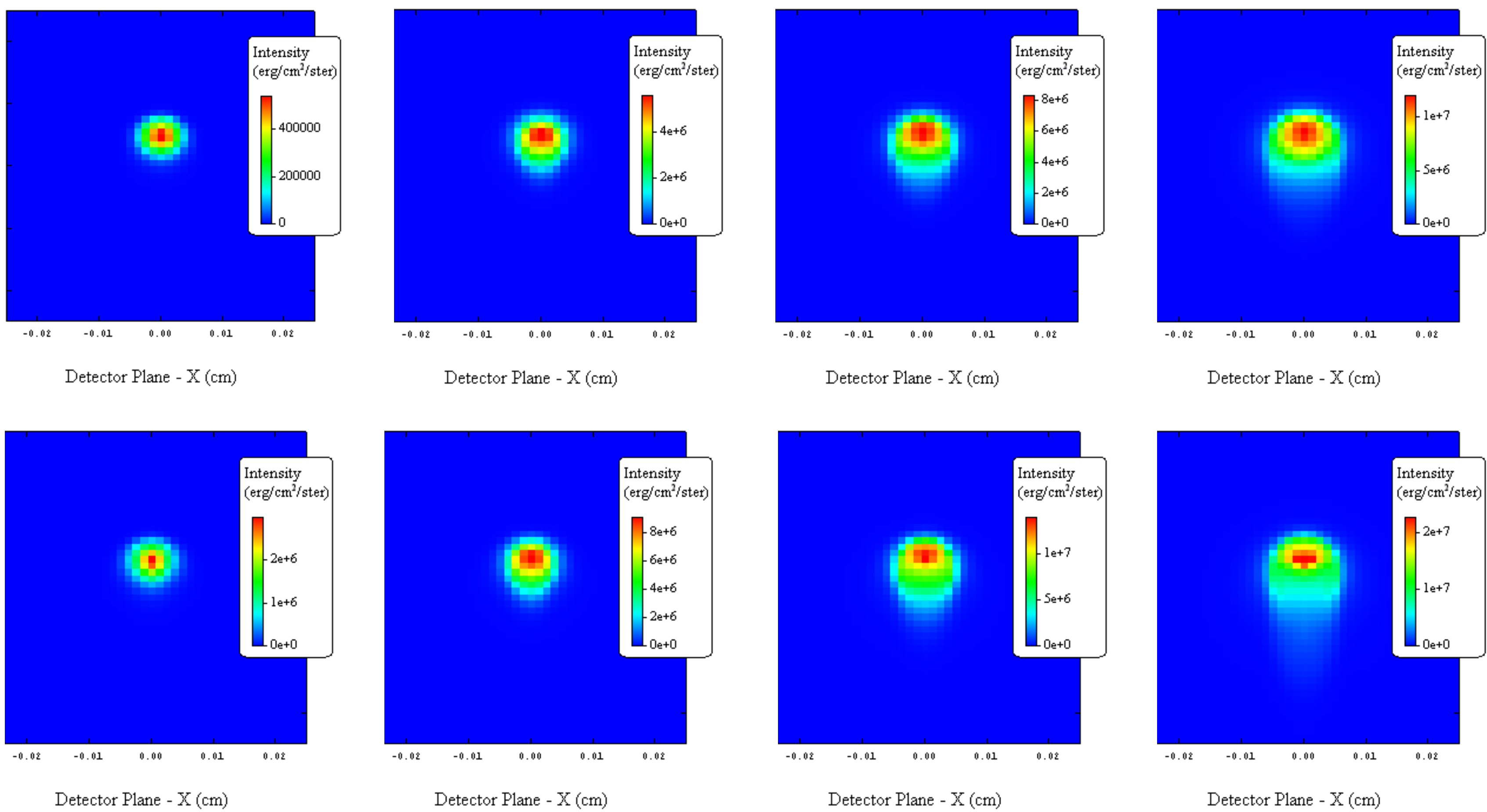
(Laser spot size = 50 µm/cm²)

100 µm

Peak intensity = 0.02 TW/cm² | 0.05 TW/cm² | 0.1 TW/cm² | 0.2 TW/cm²

10 ns FWHM

20 ns FWHM



Conclusions and Acknowledgements

- Our present work confirms previous expectations that CE and DER can be maintained with longer pulses (up to at least 30 ns)
- Modeling compares favorably with experiments in "blind trials"
  - *Both CE and DER size are in good agreement*

Funding and technical support provided by…

KLA Tencor
Accelerating Yield